Long-term variations in runoff of the Syr Darya River Basin under climate change and human activities

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Abstract: In this study, we analyzed the hydrological and meteorological data from the Syr Darya River Basin during the period of 1930–2015 to investigate variations in river runoff and the impacts of climate change and human activities on river runoff. The Syr Darya River, which is supplied by snow and glacier meltwater upstream, is an important freshwater source for Central Asia, as nearly half of the population is concentrated in this area. River runoff in this arid region is sensitive to climate change and human activities. Therefore, estimation of the climatic and hydrological changes and the quantification of the impacts of climate change and human activities on river runoff are of great concern and important for regional water resources management. The long-term trends of hydrological time series from the selected 11 hydrological stations in the Syr Darya River Basin were examined by non-parametric methods, including the Pettitt change point test and Mann-Kendall trend tests. It was found that 8 out of 11 hydrological stations showed significant downward trends in river runoff. Change of river runoff variations occurred in the year around 1960. Moreover, during the study period (1930–2015), annual mean temperature, annual precipitation, and annual potential evapotranspiration in the river basin increased substantially. We employed hydrological sensitivity method to evaluate the impacts of climate change and human activities on river runoff based on precipitation and potential evapotranspiration. It was estimated that human activities accounted for over 82.6%–98.7% of the reduction in river runoff, mainly owing to water withdrawal for irrigation purpose. The observed variations in river runoff can subsequently lead to adverse ecological consequences from an ecological and regional water resources management perspective.

Keywords: river runoff variations; water resources management; land use/land cover changes; Mann-Kendall trend test; hydrological sensitivity analysis; Aral Sea; Central Asia

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1 Introduction

During the last decade, river runoff worldwide has significantly changed owing to climate change and human activities (Shiklomanov and Georgievsky, 2002; Schneider et al., 2013), which has led to many issues (drinking water problems, rapid glacier melting, water pollution, shrinking water area or flooding, etc.) in the water resources sector. A major expected consequence of global warming is the transformation of water resources and hydrological regimes (IPCC, 2013). To better understand the variation in runoff, researchers have conducted several studies on quantifying the relative effects of climate change and human activities on runoff in many regions worldwide (Jones et al., 2006; Ma et al., 2008; Tomer and Schilling, 2009; Buendia et al., 2016; Li et al., 2016). The increase in average surface air temperature and the change of precipitation patterns may alter the regional hydrological cycle (Labat et al., 2004; Milliman et al., 2008). Moreover, factors such as water withdrawal from rivers, groundwater pumping, dam construction, and land use/land cover change can change the elements of the hydrological cycle in terms of quantity and quality both at temporal and spatial scales (Levashova et al., 2004; Ma et al., 2008). Thus, estimation of the impacts of climate change and human activities on runoff variations can make a significant contribution to water resources management (Narsimlu et al., 2013).

The Syr Darya River Basin, one of the two large basins of the Aral Sea Basin, plays an important role in Central Asia's economic and environmental development. Water resources of the river basin are more vulnerable to anthropogenic loads (regulation and distribution of flows, seizure and discharge of wastewater, etc.) and respond to climate change (Shivareva and Lee, 2012; Punkari et al., 2013; Sorokin, 2016). In the mid-1960s, the annual runoff in the basin decreased significantly (Nezlin et al., 2004; Konovalov and Williams, 2005). For example, the runoff of the Syr Darya River declined from more than 20 km^3 in 1970 to 5 km^3 and even less than 5 km^3 in 1990 (Tairov, 2015). The rapid decrease in runoff has led to reduction in the basin's discharge into the Aral Sea, thereby impacting the Aral Sea's ecology and environment (Micklin et al., 2014). According to some investigations (Dukhovny and Litvak, 1977; Abbink et al., 2005; Zou et al., 2019), researchers believed that human activities are the main causes for river runoff reduction since the 1960s, and the extent of the influence is intensifying. Nevertheless, some studies (Savitskiy et al., 2008; Unger-Shayesteh et al., 2013; Gan et al., 2015; Tursunova and Saparova, 2016; Zheng et al., 2019) also reported that the influence of climate change on river runoff is growing, thus affecting the inter-annual distribution of runoff and glaciers/snow melting rate.

Systematic quantification of the impacts of climate change and human activities on river runoff in the Syr Darya River Basin has not yet been reported. It is important to understand the hydrological responses to these changes in order to develop sustainable water management strategies. In this study, we investigated the long-term runoff variations in the Syr Darya River Basin under climate change and human activities. The objectives of this study were to (1) assess the long-term changes in river runoff in the basin; (2) detect the critical change points of annual runoff; and (3) quantitatively assess the individual contribution rates of climate change and human activities to the river runoff variations across the basin. The findings will provide a comprehensive understanding of the runoff variability and contribute to water resources management and planning in the Syr Darya River Basin.

2 Study area and methods

2.1 Study area

The Syr Darya River Basin (39°23′–46°00′N, 61°00′–78°24′E; Fig. 1) is one of two large river basins in the Aral Sea Basin in Central Asia and drains approximately 0.219×10^6 km^2 (32% of the whole territory of Central Asia). The basin includes territories of four countries, namely Kyrgyzstan, Uzbekistan, Tajikistan, and Kazakhstan (CAREWIB, 2011). The Syr Darya River originates from the Tianshan Mountains, flows through the steppe and the Kyzylkum Desert, and finally arrives at the Small Aral Sea (Stucker et al., 2012).

The upper part of the basin belongs to the zone of natural runoff formation zone, which is located in non-irrigated land in the upper ridge valleys of the Tianshan Mountains and Alai Mountains. The middle reaches are located in alluvial valleys (Fergana and Chirchik), where the runoff is influenced by reused wastewater from irrigated land and other forms of agricultural activities. The lower reaches of the basin, located downstream of the Chardara Reservoir, are in the flow dissipation zone. Runoff is used for a variety of industrial needs in the middle and lower reaches of the basin, mainly for irrigation (Nezlin et al., 2004; Petrov and Akhmedov, 2011). The major developments of the basin are listed in Table 1.

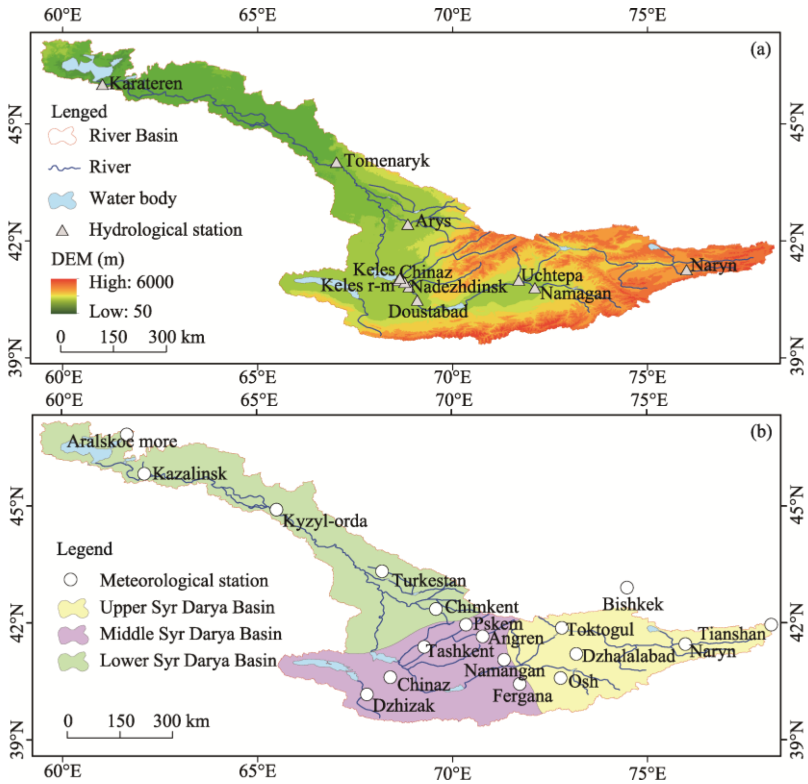

Fig. 1 Overview of the Syr Darya River Basin (a and b) as well as the locations of hydrological stations (a) and meteorological stations (b). DEM, digital elevation model.

Table 1 Major developments of the Syr Darya River Basin

Year	Development of water conservancy facility	Description
1930	Big Fergana Canal was put into operation	Capacity of headwork: 200 m^3/s
1930	North Fergana Canal was put into operation	Capacity of headwork: 110 m^3/s
1951	South Golodnostep Canal was put into operation	Capacity of headwork: 300 m^3/s
1959	Kairakum Reservoir was built and put into operation	Purpose: irrigation and energy; river: Syr Darya; nominal volume: 5.2 $\times 10^9$ m^3
1965	Chardara Reservoir was built and put into operation	Purpose: irrigation and energy; river: Syr Darya; nominal volume: 4.0 $\times 10^9$ m^3
1963–1972	Charvak Reservoir was built and put into operation	Purpose: irrigation and energy; river: Chirchik; nominal volume: 2.0 $\times 10^9$ m^3
1978	Andijan Reservoir was built and put into operation	Purpose: irrigation and energy; river: Karadarya; nominal volume: 1.9 $\times 10^9$ m^3
1982	Toktogul Reservoir was built and put into operation	Purpose: irrigation and energy; river: Naryn; nominal volume: 19.5 $\times 10^9$ m^3

The study area is characterized by a typical temperate continental climate with annual mean temperature ranging from –10 ℃ to 5 ℃ in the mountainous area and –10 ℃ to 15 ℃ in the desert area in the downstream of the river basin. Snow accounts for a significant proportion of

precipitation, and there are also glaciers in some areas of the basin. The long-term mean annual precipitation is approximately 500 mm in the upstream, 300 mm in the mid-stream area, and 100–150 mm in the downstream of the river basin. The long-term mean annual potential evapotranspiration (PET) fluctuates from 1000 to 1500 mm.

Owing to its inland location and remoteness from the world's oceans, Central Asia is characterized by an arid and semi-arid climate with insufficient soil moisture and low relative humidity (Qi et al., 2012). Thus, the Syr Darya River basin is an arid region in the world. As a result of changes in climate, water resources, and land use/land cover, the Syr Darya River Basin is experiencing an increasingly strong water deficit, as illustrated by the rapid shrinkage and degradation of the Aral Sea (Jiang et al., 2017; Guo et al., 2018).

2.2 Datasets

Runoff, air temperature, and precipitation data of the Syr Darya River Basin from 1930 to 2015 were collected in this study. The runoff data of the Syr Darya River Basin were collected from 11 hydrological stations (Fig. 1; Table 2) with long-term observational data sequences for hydrological studies. Five stations were located along the Syr Darya River and six stations were located in the major tributaries. To analyze the changes in runoff, we selected three stations as control stations for each part of the basin. Tomenaryk station is the control area of the whole basin (98% of the total area of the Syr Darya River Basin), which is located in the downstream of the basin. Keles hydrological station is located before the entrance of the Syr Darya River to the Chardara Reservoir, after which the lower reaches of the basin begin. Namangan station is located at the beginning of the Syr Darya River, which is the confluence of two large rivers at the exit from the mountainous region. Additionally, Naryn station (Naryn River sub-basin) was selected to analyze the changes of runoff in the mountainous region and sub-basins of the Syr Darya River Basin.

Table 2 Hydrological stations of the Syr Darya River Basin

Region	Hydrological station	River	Distance to the mouth (km)	Altitude (m)
Upstream	Naryn	Naryn	534.0	2040.3
	Uchtepa	Karadarya	8.0	405.3
	Namagan	Syr Darya	2173.0	377.6
Mid-stream	Doustabad	Angren	19.0	294.0
	Chinaz	Chirchik	3.2	252.0
	Keles	Syr Darya	1732.0	246.0
	Nadezhdinsk	Syr Darya	1812.0	263.0
	Keles river mouth	Keles	1.2	250.0
Downstream	Arys	Arys	126.0	222.2
	Tomenaryk	Syr Darya	996.0	157.7
	Karateren	Syr Darya	-	42.0

Note: -, no data available.

Eighteen meteorological stations were selected within the basin and the surrounding areas. Given the limited availability and lack of observational data over the Syr Darya River Basin, we used freely available datasets in this study. Gridded mean annual PET datasets were collected from the Climatic Research Unit (CRU TS4.00; http://www.cru.uea.ac.uk/data/). The CRU dataset was chosen for several reasons. We created this gridded dataset based on a large number of stations and these stations have good quality control and homogeneity verification (Mitchell and Jones, 2005). The CRU dataset has a spatial resolution of 0.5° and covers land areas of the Earth (Harris et al., 2014). Recent studies have proposed that the CRU high-resolution dataset is satisfactory and applicable for hydroclimatological researches in Central Asia (Deng and Chen, 2017; Guo et al., 2018; Zou et al., 2019).

Data on land use/land cover and its major developments were obtained from the Regional Information System on Water and Land Resources in the Aral Sea Basin (http://www.cawater-info.net).

2.3 Methods

2.3.1 Trend test

The non-parametric Mann-Kendall trend test (Mann, 1945; Kendall, 1948) was used for identifying trends in the time series data. This method compares the relative magnitudes of the sample data rather than the data values themselves (Gilbert, 1987). It is not necessary to conform to any particular distribution in the Mann-Kendall trend test, and it has a low sensitivity to abrupt breaks due to inhomogeneous time series, which makes it more suitable for trend tests (Jaagus, 2006). The statistical processes can be explored as follows:

$$S=\sum_{k=1}^{n-1}\sum_{j=k+1}^{n}\mathrm{sgn}(x_j-x_k), \tag{1}$$

$$\mathrm{sgn}(x_j-x_k)=\begin{cases}1,\ \text{if}\ \ x_j-x_k>0\\ 0,\ \text{if}\ \ x_j-x_k=0\\ -1,\ \text{if}\ \ x_j-x_k<0\end{cases}, \tag{2}$$

$$\mathrm{Var}(S)=\frac{\left[n(n-1)(2n+5)-\sum_t t(t-1)(2t+5)\right]}{18}, \tag{3}$$

where x_j and x_k are the annual data values at times j and k, respectively; n is the length of observation; and t is the extent of any given time. The parameter Z conforms to the standard normal variable and can be calculated by the following equation:

$$Z=\begin{cases}\dfrac{S-1}{\sqrt{\mathrm{Var}(S)}},\ \text{if}\ S>0\\ 0,\ \text{if}\ S=0\\ \dfrac{S+1}{\sqrt{\mathrm{Var}(S)}},\ \text{if}\ S<0\end{cases}. \tag{4}$$

A positive Z value represents increasing trends while a negative Z value indicates decreasing trends. The H_0 hypothesis of Z>1.96 is rejected when testing either increasing or decreasing monotonous trends at a 5% significance level (Tabari et al., 2011).

The Mann-Kendall trend test expects that the time series data should be independent. However, hydrological time series often display statistically significant serial correlations. Thus, in order to detect serial correlations, we applied the pre-whitening process in accordance with Yue and Wang (2004), who have suggested that the variance correction approach could be used to address the issue of serial correlation in trend analysis. In this study, we removed trend from the series and calculated effective sample size using significant serial correlation coefficients.

2.3.2 Pettitt change point test

The Pettitt change point test is a non-parametric test for detecting an abrupt or significant changes (Pettitt, 1979) in a time series. The test has been commonly used to detect changes in observed climatic and hydrological time series (Gao et al., 2011; Belihu et al., 2018).

It considers a time series as two samples represented by x_1, x_2, …, x_t and x_{t+1}, x_{t+2}, …, x_n. The Pettitt index $U_{t,n}$ is given by Equation 5:

$$U_{t,n}=\sum_{j=1}^{t}\sum_{i=1}^{T}\mathrm{sgn}(x_i-x_j)\ (t=1, 2, ..., n), \tag{5}$$

where the maximum $U_{t,n}$ indicates the change point year.

2.3.3 Double cumulative curve

The double cumulative curve was applied to determine the time when human activities began to clearly influence the upstream and/or downstream runoff. The double cumulative curve between precipitation and total runoff (Searcy and Hardison, 1960) for each part of the basin was used to

detect the effects of human activities on runoff in the downstream, midstream, and upstream of the river basin.

2.3.4 Quantification of the impacts of climate change and human activities on river runoff

Climate change and human activities are the two main factors affecting the hydrology change in the basin. In this study, we attempted to consider their separate influences on river runoff variations. The individual influence of climate change and human activities on runoff variations was estimated by the following equation:

$$\Delta R_{total}=\Delta R_{clim}+\Delta R_{hum}, \tag{6}$$

where ΔR_{total} (mm) is the variation of river runoff; ΔR_{clim} (mm) and ΔR_{hum} (mm) are the variations of river runoff due to climate change and human activities, respectively.

The hydrological sensitivity analysis method explains the percentage change in annual runoff response to the variability of annual precipitation and PET. Generally, the basin's water balance can be represented as follows:

$$P = AET + R + \Delta S, \tag{7}$$

where P (mm) is the precipitation; AET (mm) is the actual evapotranspiration; R (mm) is the river runoff; and ΔS (mm) is the change in the water storage (ΔS can be assumed as zero for a long time series). Following the equation of Zhang et al. (2001), the AET can be described using the following equation:

$$\frac{AET}{P} = \frac{1 + w(\frac{PET}{P})}{1 + w(\frac{PET}{P}) + (\frac{PET}{P})^{-1}}, \tag{8}$$

where w is the available water coefficient of vegetation; and PET is the potential evapotranspiration (mm).

Changes in annual P and PET can result in water balance variations. Therefore, we obtained the ΔR_{clim} based on hydrological sensitivity analysis method proposed by Milly and Dunne (2002):

$$\Delta R_{clim} = \beta \Delta P + \gamma \Delta PET, \tag{9}$$

where β and γ represent the sensitivity coefficients of runoff to precipitation and PET, respectively (Li et al., 2007), which can be calculated as follows:

$$\beta = \frac{1 + 2x + 3wx}{(1 + x + wx^2)^2}, \tag{10}$$

$$\gamma = -\frac{1 + 2wx}{(1 + x + wx^2)^2}, \tag{11}$$

where x is the dryness index, which is equal to PET/P.

ΔR_{clim} can be easily acquired by Equation 9, so ΔR_{hum} is determined by Equation 6. The contributions of climate change and human activities on river runoff were calculated by Equations 12 and 13, respectively:

$$I_{clim}(\%) = \frac{\Delta R_{clim}}{\Delta R_{total}} \times 100\%, \tag{12}$$

$$I_{hum}(\%) = \frac{\Delta R_{hum}}{\Delta R_{total}} \times 100\%, \tag{13}$$

where I_{clim} (%) and I_{hum} (%) are the percentages of river runoff variations due to climate change and human activities, respectively.

3 Results and discussion

3.1 Changes in temperature, precipitation, and potential evapotranspiration (PET)

Changes in annual mean temperature, annual precipitation, and annual PET from 1930 to 2015

are shown in Figure 2 and Table 3. During the study period, mean annual precipitation varied from 135 mm (downstream) to 363 mm (upstream) in the Syr Darya Basin. Annual mean temperature ranged from 5.2 ℃ to 14.1 ℃, and mean annual PET varied from 893 mm in the upstream area to 1396 mm in the downstream of the basin.

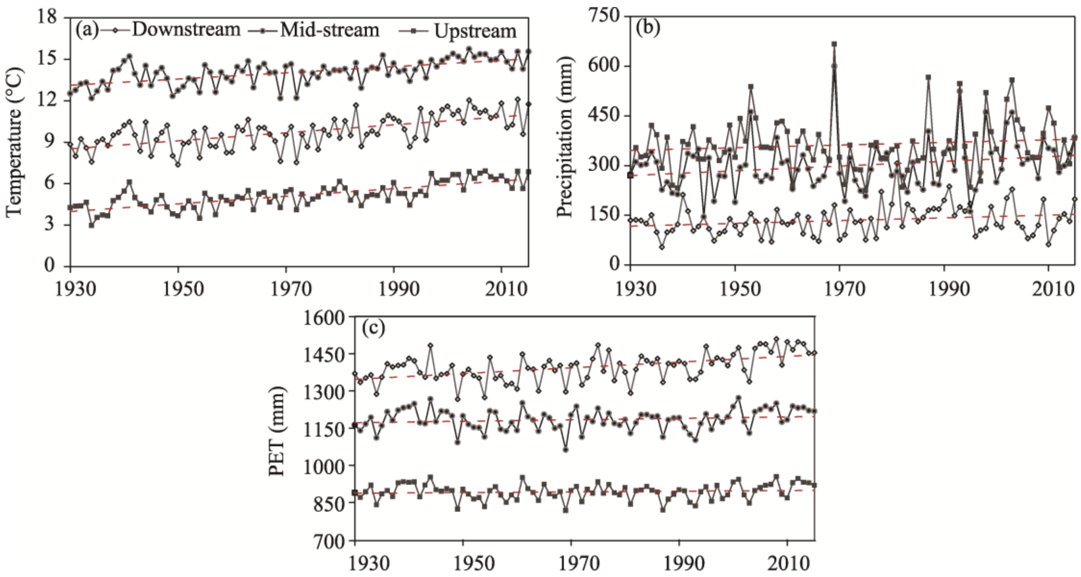

Fig. 2 Change trends of annual mean temperature, annual precipitation, and annual potential evapotranspiration (PET) in the downstream, mid-stream, and upstream of the Syr Darya River Basin during the period of 1930–2015

Table 3 Results of trend test and change point analyses of temperature, precipitation, and potential evapotranspiration (PET) in the downstream, mid-stream, and upstream of the Syr Darya River Basin

Region	Factor	Trend rate	*Z* value	Change point	Significance level
Upstream	Temperature (℃/10a)	0.30	12.10	1976	0.01
	Precipitation (mm/10a)	3.98	1.33	1997	*
	PET (mm/10a)	1.40	1.64	1999	*
Mid-stream	Temperature (℃/10a)	0.20	10.70	1984	0.01
	Precipitation (mm/10a)	7.10	6.56	1989	0.01
	PET (mm/10a)	2.90	2.51	1998	0.05
Downstream	Temperature (℃/10a)	0.30	9.61	1978	0.01
	Precipitation (mm/10a)	4.20	4.03	1977	0.01
	PET (mm/10a)	11.50	6.81	1973	0.01

Note: *, non-significant. *Z* value, change point, and significance level are dimensionless.

Results of the Mann-Kendall trend test (Table 3) showed that annual mean temperature increased significantly in the Syr Darya River Basin from 1930 to 2015 ($P<0.01$), with an average increase rate of 0.26 ℃/10a. This rate was much higher than the global average temperature (at a rate of 0.13 ℃/10a) and average increasing rate of Central Asia (at a rate 0.16 ℃/10a) (Brohan et al., 2006; Mannig et al., 2013). Precipitation and PET exhibited remarkable increasing trends with the rates of 4.10–7.10 mm/10a ($P=0.01$) and 11.00 mm/10a ($P=0.05$), respectively, except the upstream of the basin. Some studies have pointed out that increasing temperature, westerly cyclones southward shift and its deepening, and the changes of water vapor at the middle latitudes are probably the main factors that rising the precipitation over Central Asia (Lioubimtseva and Cole, 2006; Chen et al., 2011). The results from the Pettitt change point test showed that there was a statistically significant upward shift in all the meteorological time series, except for the upstream of the basin (Table 3). Although the change points occurred in different years, those

for most areas were between 1978 and 1999.

As noted in several studies in recent decades, the increase of surface temperatures has led to a higher melting rate and a significant shrinkage of glaciers; this trend will continue in the future (e.g., Sorg et al., 2014). It is expected that, the river runoff will either slightly increase or will not change beyond the variability in runoff (Reyer et al., 2017).

3.2 Human activities

Human activities in this study were mainly analyzed in terms of land use/land cover changes (mainly an increase in irrigated land). Land use/land cover can be divided into seven types in the study area, including cropland, forest land, grassland, shrubland, urban land, water body, and bare land. The spatial distributions of land use/land cover types in the study area in 1995 and 2015 are shown in Table 4. Grassland and cropland were the major types of land use/land cover, occupying more than 65.0% of the total study area. Area of cropland respectively accounted for 16.5% and 15.0% of the basin area in 1995 and 2015, of that about 80% was irrigated. The proportions of grassland area in 1995 and 2015 were 48.8% and 50.7%, respectively. From 1995 to 2015, the urban land area increased by 466.7% and exhibited a rapid expansion. By contrast, bare land decreased by 9.6% within these 21 years. Both forest land and shrubland areas were reduced from 1995 to 2015, albeit not significantly.

Table 4 Area of land use/land cover types in the Syr Darya River Basin in 1995 and 2015

Year	Grassland (10^3 km^2)	Bare land (10^3 km^2)	Cropland (10^3 km^2)	Shrubland (10^3 km^2)	Forest land (10^3 km^2)	Water body (10^3 km^2)	Urban land (10^3 km^2)
1995	141.5	55.1	47.8	24.1	15.1	5.8	0.6
2015	144.2	49.8	42.8	24.0	14.0	6.2	3.4

With the continuous increase in population (http://pop-stat.mashke.org) and the development of agricultural industry (Rubinova, 1979), the impacts of water-related human activities, especially agricultural production activities, on the Syr Darya River Basin had been intensified in the past 50 years. In the Syr Darya River Basin, water-related human activities mainly refer to extracting surface water to meet the continuous expansion of irrigated agricultural land. The irrigation area in the Syr Darya River Basin has increased from 0.99×10^6 hm^2 in 1930 to 2.04×10^6 hm^2 in 1960 and to 3.12×10^6 hm^2 in 2015, which increased the total water withdrawal from the river basin. As shown in Figure 3, the total water withdrawal in the Syr Darya River Basin increased by 50% from 1960 to1980 and deceased by 29% from 1980 to 2013.

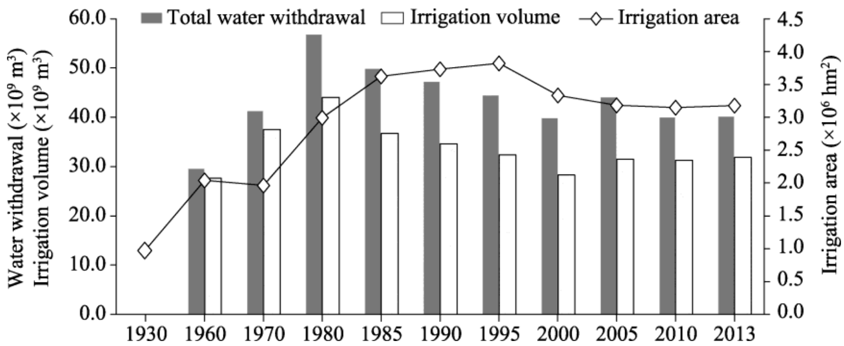

Fig. 3 Changes of total water withdrawal, irrigation volume, and irrigation area in the downstream, mid-stream, and upstream of the Syr Darya River Basin from 1930 to 2013

3.3 Changes in annual river runoff

The mean annual river runoff of the 11 selected hydrological stations was tested using the Mann-Kendall method, and the results are shown in Table 5. Eight hydrological stations showed significant decreasing trends of annual river runoff, while the remaining three stations showed no significant trends of annual river runoff.

The annual river runoff in the Syr Darya River Basin showed remarkable negative trends during the period of 1930–2015, with the decreasing rates of 6.1 mm/10a (Tomenaryk station), 8.7 mm/10a (Keles station), and 4.5 mm/10a (Namagan station) in the downstream, mid-stream, and upstream, respectively. The time series of annual river runoff for the four selected hydrological stations in the basin is shown in Figure 4.

Table 5 Results of trend test and change point analyses of annual river runoff in the Syr Darya River Basin

Region	Hydrological station	Z value	Change point	Significance level
Upstream	Namagan	–3.1	1960	0.01
	Naryn	–1.6	1960	*
	Uchkurgan	0.2	-	*
Mid-stream	Nadezhdinsk	–3.3	1960	0.01
	Keles	–3.7	1964	0.01
	Doustabad	–5.4	1960	0.01
	Chinaz	–4.6	1960	0.01
	Keles river mouth	1.2	1992	*
Downstream	Tomenaryk	–3.6	1964	0.01
	Karateren	–3.9	1964	0.01
	Arys	–3.6	1964	0.01

Note: *, non-significant; -, no data available.

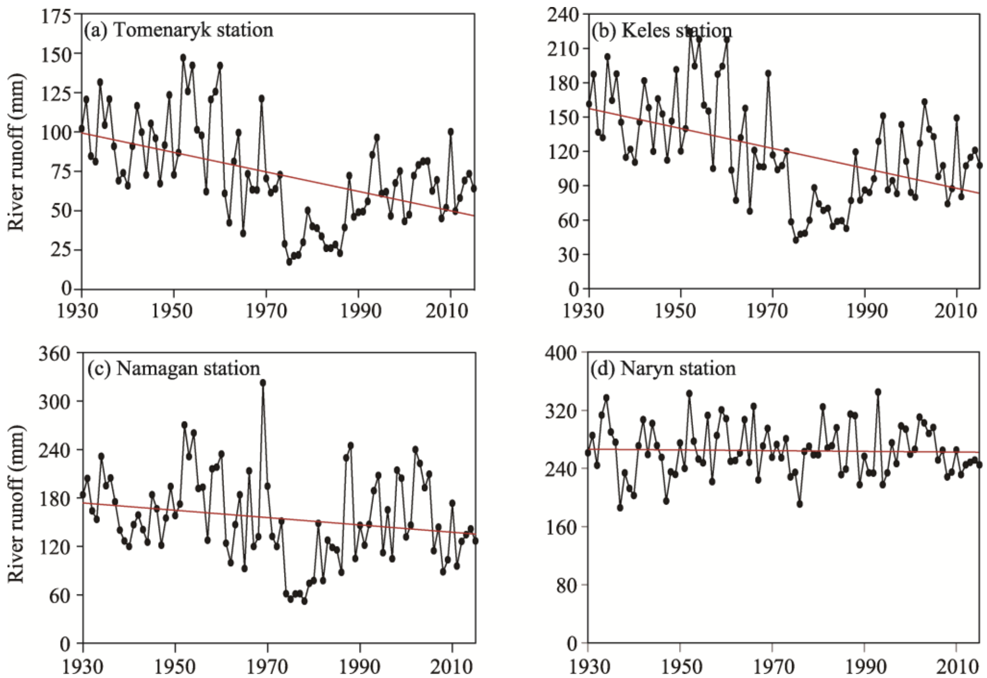

Fig. 4 Long-term variations of annual river runoff in the Syr Darya River Basin from 1930 to 2015. (a), Tomenaryk station; (b), Keles station; (c), Namagan station; (d), Naryn station.

From 1970 to 1990, the river runoff was characterized by the lowest flow values (Fig. 4). During these years, there was a sharp development in the Syr Darya River Basin, for example, the reclamation of newly irrigated lands and the operation of the Toktogul Reservoir, among other activities. However, it was observed that the river runoff begun to increase over the past 30 years. The runoff in the period of 1990–2015 increased by 2.0, 3.0, and 1.6 mm in the downstream, mid-stream, and upstream of the Syr Darya River Basin, respectively.

The Pettitt change point test and double cumulative curve method were applied to explore the

abrupt change point of annual river runoff. The computed probability series of abrupt change point years is shown in Table 5 and the double cumulative curve of annual river runoff is shown in Figure 5. Results shown in Table 5 indicated that most abrupt change points occurred in 1960 and 1964 (at a 0.01 significance level). Moreover, the double cumulative curves demonstrated in Figure 5 implied that river runoff and precipitation were relatively uniform before 1964 and 1966 in the downstream and upstream, respectively; and thereafter, both of them showed variations. Taken together, we speculate that the year 1960 could be the abrupt change year when climate change and human activities began to impact river runoff. Therefore, the phase 1930–1960 was taken as the baseline period during which climate change and human activities had less impacts on water resources. The main reason for the variations of river runoff and precipitation may be the construction and operation of the Kairakum and Chardara reservoirs, as well as the construction of irrigation canals in the upstream of the basin.

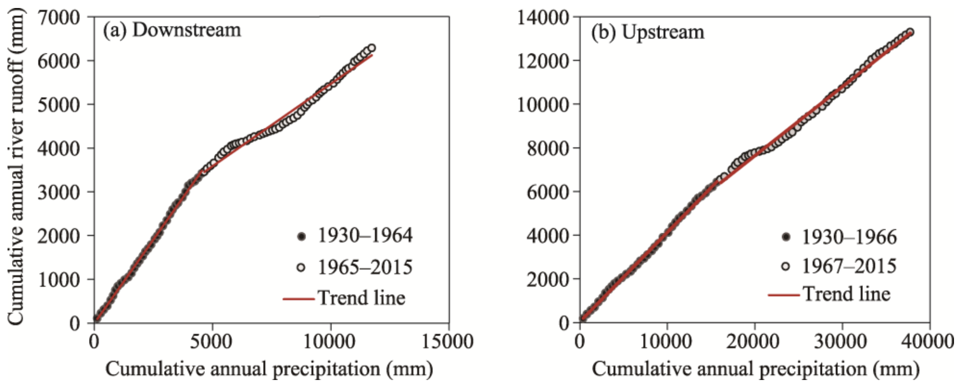

Fig. 5 Double cumulative curves of annual river runoff and annual precipitation in the downstream (a) and upstream (b) of the Syr Darya River Basin during the period of 1930–2015

3.4 Contributions of climate change and human activities to the variations of river runoff

River Runoff reduction during the study period could be attributed to the combined effects of climate change and human activities. We divided the whole study period (1930–2015) into five phases according to the above-mentioned analysis and the development of human activities: 1930–1960 (baseline period), 1961–1975 (the construction period of water conservancy facilities), 1976–1990 (period of intensive land use), 1991–2005 (post-Soviet period), and 2006–2015 (present). Variations of precipitation, PET, and river runoff for each period were analyzed (Table 6). It was found that precipitation across the whole basin generally showed an increasing trend. However, decreasing trends occurred in some periods and in some regions, for example, the period of 1961–1975 in the upstream of the basin, and the periods of 1961–1975 and 1976–1990 in the downstream of the basin. PET in the downstream of the basin all showed increasing trends; it also showed increasing trends in the upstream and mid-stream, with the exceptions of 1961–1975 and 1976–1990 (in the upstream), in which decreasing trends were recorded.

Generally, human activities were the dominant factor affecting river runoff of the Syr Darya River Basin. Nevertheless, there was an increase in the impact of climate change on river runoff in the 1991–2005 period compared with other periods. The reason for this difference could be explained by the change in the economic situation and the increase in precipitation in the Syr Darya River Basin during these years. Regarding the Naryn River sub-basin, human activities played a dominant role in the decline of river runoff during the periods of 1961–1975 and 2006–2015, contributing 52.0% and 59.0% of river runoff variations, respectively.

In respect to the impacts of climate change on river runoff, it had a negative influence during certain periods. For instance, climate change showed a negative effect on river runoff during the periods of 1961–1975 and 2006–2015 in the downstream of the basin. Similarly, climate change

also showed a negative influence on river runoff during the periods of 1961–1975 and 2006–2015 in the Naryn River sub-basin (Table 6).

Table 6 Variations of precipitation, PET, and river runoff as well as relative contributions of climate change and human activities on variations of river runoff in the Syr Darya River Basin during the period of 1961–2015

Region	Period	ΔP (mm)	ΔPET (mm)	ΔR (mm)	ΔR_{clim} (mm)	ΔI_{clim} (%)	ΔR_{hum} (mm)	ΔI_{hum} (%)
Upstream	1961–1975	–5.2	–3.9	–36.2	–4.0	9.0	–40.2	91.0
	1976–1990	0.9	–2.6	–64.3	0.8	1.2	–65.1	98.8
	1991–2005	23.0	3.8	–5.6	19.1	43.6	–24.7	56.4
	2006–2015	5.3	35.5	–54.7	1.1	1.9	–55.7	98.1
	1961–2015	6.1	5.7	–38.9	3.9	8.4	–42.8	91.6
Mid-stream	1961–1975	0.0	–1.3	–52.5	–0.1	0.1	–52.6	99.9
	1976–1990	3.8	–2.2	–90.4	1.9	2.1	–92.3	97.9
	1991–2005	49.4	1.0	–46.2	37.9	31.1	–84.0	68.9
	2006–2015	42.1	41.2	–55.1	30.0	26.1	–85.1	73.9
	1961–2015	22.2	6.8	–61.6	16.4	17.4	–78.0	82.6
Downstream	1961–1975	0.2	23.1	–37.3	–0.1	0.3	–37.2	99.7
	1976–1990	44.9	28.7	–64.6	0.7	1.0	–65.3	99.0
	1991–2005	32.5	49.4	–34.1	1.2	3.3	–35.3	96.7
	2006–2015	7.3	105.4	–36.7	–0.2	0.5	–36.5	99.5
	1961–2015	22.5	46.8	–43.8	0.6	1.3	–44.4	98.7
Naryn River sub-basin	1961–1975	–21.6	2.5	–2.4	–27.6	48.0	–30.0	52.0
	1976–1990	–0.3	–3.4	–1.3	–0.9	68.0	–0.4	32.0
	1991–2005	31.1	–2.2	7.1	31.7	56.0	–24.6	44.0
	2006–2015	–10.1	30.1	–19.6	–8.0	41.0	–11.6	59.0
	1961–2015	0.7	4.6	–2.6	1.4	55.0	–1.2	45.0

Note: ΔP, variations of precipitation; ΔPET, variations of potential evapotranspiration; ΔR, variations of river runoff; ΔR_{clim}, variations of river runoff due to climate change; ΔI_{clim}, percentage of river runoff variations due to climate change; ΔR_{hum}, variations of river runoff due to human activities; ΔI_{hum}, percentage of river runoff variations due to human activities.

3.5 Impacts of climate change and human activities on river runoff

Human factor plays a significant role in influencing river runoff of the basin. Despite this, river runoff also showed sensitivity to changes of precipitation. The sensitivity of river runoff to precipitation (0.80–2.00) was indeed greater than that of river runoff to PET (0.14) in the Syr Darya River Basin, with an exception of the downstream. This means that precipitation had a greater potential to affect river runoff. In addition, when the precipitation in the post-change period was less than that in the baseline period, the result of variations of river runoff due to human activities was negative. During the period of 1991–2005, the value of precipitation was higher than that in the baseline period, and then river runoff showed a positive value. This period (1991–2005) was characterized by a large amount of precipitation (Song and Bai, 2016; Li et al., 2017). Furthermore, during this period (after the collapse of the Soviet Union), area of irrigated land reduced and water withdrawals for irrigation correspondingly decreased as a result of the reorganization of state farms and collective farms into small farms (Amirgaliev et al., 2008; Han et al., 2012). Moreover, there was a significant positive correlation between precipitation and river runoff (Fig. 6).

We also considered the relationships of river runoff with irrigation area and water withdrawal (Fig. 6). A significant correlation was found between river runoff and irrigation area, with correlation coefficients of 0.50–0.53. The correlation coefficients between river runoff and water withdrawal were –0.40 and –0.43 for the mid-stream and downstream of the basin, respectively. Moreover, the *P* values were less than 0.05, which indicated that the correlations between variations of river runoff and cultivated land areas/water withdrawal were significant. However, river runoff showed weak, non-significant correlations with other non-irrigated land.

Additionally, the reduction in river runoff in the study area was also affected by the construction of large-scale reservoirs (Rubinova, 1979; Antipova et al., 2002). During the initial impoundment period, the reservoir could reduce river runoff; however, when the reservoir is full of water, it also results in more evaporation and changes the hydrological regime of the river and the level of groundwater in the basin, affecting the water quality (Biemans et al., 2011). With the growth of irrigated land, river runoff is mostly used to meet the demand of irrigation water resources, thus reducing river runoff (Shonbayeva et al., 2015). This reduction in river runoff will lead to water shortage and influence the security of water supply in Central Asia.

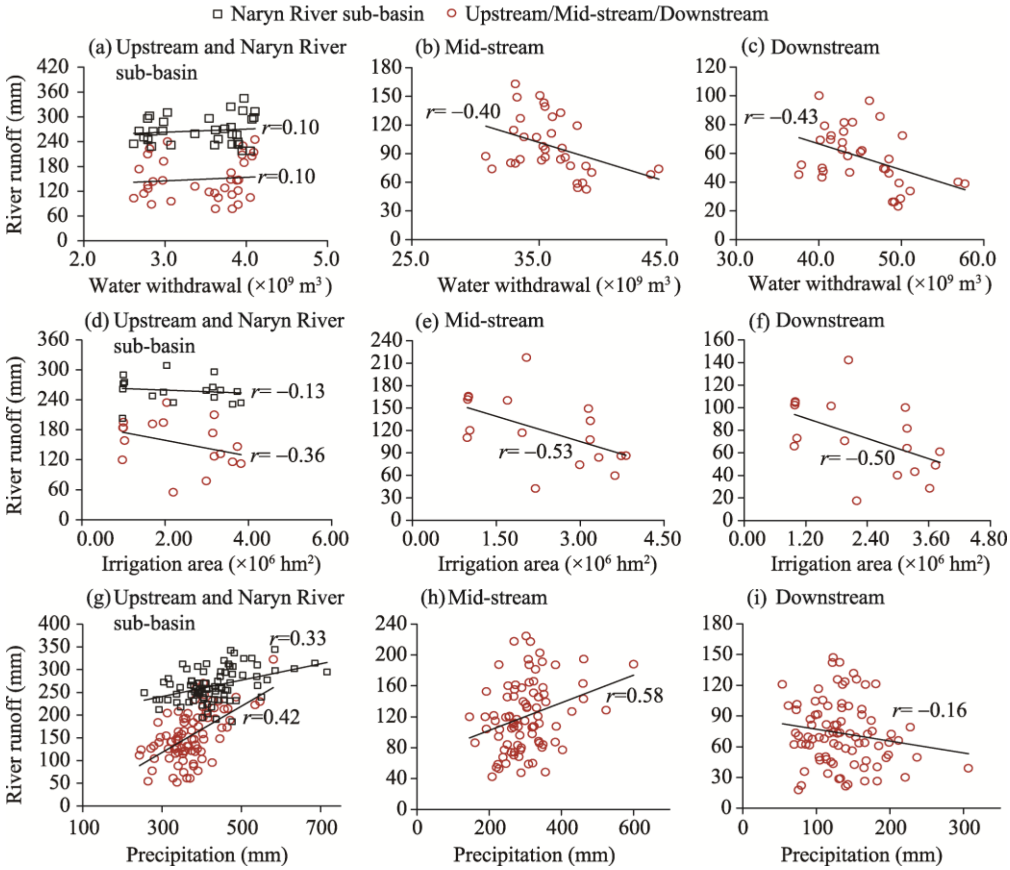

Fig. 6 Relationships of river runoff with water withdrawal (a, b, c), irrigation area (d, e, f), and precipitation (g, h, i) in the upstream, mid-stream, downstream, and Naryn River sub-basin of the Syr Darya River Basin

4 Conclusions

In this study, we studied the variations of runoff in the Syr Darya River Basin of Central Asia under climate change and human activities during the period of 1930–2015. During the study period, annual mean temperature in the whole region showed a noticeable increasing trend at a rate of 0.27 ℃/10a, while both annual precipitation and PET showed an increasing tendency in the basin, except for the upstream. River runoff in the Syr Darya River basin exhibited a significant decreasing tendency (P<0.01) during the period of 1930–2015, and change point was identified around 1960. Taken the period of 1961–2015 as a whole, results of the impacts of climate change and human activities on river runoff indicated that human activities were the dominant factor that resulted in the decrease of river runoff, with contribution rates of 82.6%–98.7%, while climate change only accounted for 1.0%–17.4%. Regarding the Naryn River sub-basin (mountainous area), climate variation contributed 55.0% to the variations of river runoff.

Variations of river runoff in the Syr Darya River Basin should be taken into account in future water resources planning and management, especially in the context of planned large-scale irrigation use in the mid-stream and downstream areas of the basin and hydroelectric power stations in the upstream.

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